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STRUCTURAL IRON IN GREEK ARCHITECTURE

An allusion to the employment of structural iron in Greek architecture would naturally impress us as paradoxical. We are accustomed, to be sure, to the small iron members which the Greek stone-masons substituted for mortar as a bonding material between blocks of stone. Such small members may readily be classified to form three groups: first, there were iron clamps to fasten together stones in the same course; second, there were iron dowels to fasten stones to the course below them; and third, there were iron braces, primarily to brace stones in position while they were being doweled, but never afterwards removed.[1] Yet while, at first thought, we might be tempted to regard Greek structural iron as consisting solely of dowels and clamps (a few of us might remember the braces), it is not with these that we are now concerned; I wish to discuss quite another phase of the subject, a phase more analogous to the modern use of structural steel.

We are accustomed to regard Greek construction as a simple piling up of stones, their superstructures as a simple piling up of beams. Such, for instance, is the general conclusion of the French critic Choisy. Yet, if we pause for consideration, most of us will remember instances which show a technical knowledge far in advance of what Choisy's words would imply, a technical knowledge such as Durm dismissed as "quite impossible, . . . in the manner of the late Baroque period."[2] For lack of space I must omit the whole field of masonry construction, with such delicate problems as those of balancing, of hollowing to diminish weight, of increasing the thickness at the weakest point. There are marble flanged beams at Samothrace which might have served as patterns for steel beams being made today in the rolling mills of Pennsylvania. I must limit myself rather to a smaller but more incongruous field, incompatible with our general notions of

[1] Concerning dowels and clamps, see Stevens, in Fowler and Wheeler, *Handbook of Greek Archaeology*, pp. 104–107; concerning braces, see Orlandos, 'Preliminary Dowels,' *A.J.A.* XIX, 1915, pp. 175–178.

[2] Durm, *Baukunst der Griechen* (1910), pp. 403, 545.

Greek architecture, that of construction in iron.[1] I shall cite merely a few instances, some new, others already well known, but so arranging them as to show the degree of Greek attainment in this direction.

Let me begin with some very simple instances. The acroteria at the angles of the gables, in the oldest temple of Athena on the Acropolis, as identified a few years ago by Schrader,[2] are merely thin slabs of marble, jointed together with mortise and tenon, a form of construction which, like that of the temple as a whole, reminds us strongly of carpentry in wood. These board-like slabs, leopards at the lower corners, a Gorgon on each apex, would hardly have stood without assistance, and this was supplied in the form of long iron stay-rods or braces, which sloped from the back of each figure down to the roof behind.

Another example of reinforcement occurred in the Theban Treasury at Delphi. The foundations of this structure, constructed of a soft limestone, were laid upon a steep slope at a point swept by the miniature river which poured down the Sacred Way on rainy days. Such foundations, though purposely made very thick (5 ft.), were in need of reinforcement, and this was provided by great iron bars, 41 ft. long on each flank, and about $18\frac{1}{2}$ ft. long at each end of the building, overlapping at the corners and hooked over each other in such a way as to provide a firm rectangular frame measuring about $39\frac{3}{4} \times 17\frac{1}{4}$ ft. in plan. The bars themselves were $3\frac{1}{4}$ inches high and 4 inches wide, the width being the greater because the purpose was to prevent lateral displacement. Of these bars nothing

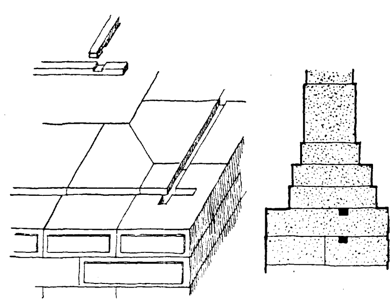

FIGURE 1.—FOUNDATION OF THEBAN TREASURY: DELPHI.

[1] An 'Essai sur l'existence d'une architecture metallique antique' was published many years ago by Charles Normand (*Encyclopédie d'Architecture*, 3rd series, II, 1883, pp. 61–80; cf. *R. Arch.*, 3rd series, VI, 1885, pp. 214–223). So far as Greek architecture is concerned, however, M. Normand speaks only of dowels and clamps, and of decorative accessories which lie outside our province.

[2] Schrader, *Archaische Marmor-Skulpturen im Akropolis-Museum zu Athen*, pp. 5–16; Dickins, *Catalogue of the Acropolis Museum*, I, Nos. 122, 551–555, 701.

now remains except the grooves which formed their beds in the top course of the foundation, and the weathered traces on the bottom of the lowest step of the crepidoma, which rested directly upon the bar and was doweled to it (Fig. 1).[1] And there are indications of a similar system of reinforcement in the second course of the foundation.

Quite different in purpose, acting rather as beams, were the well-known examples found in the great temple of Zeus at Acragas, in Sicily. Here each bay of the architrave, on account of its

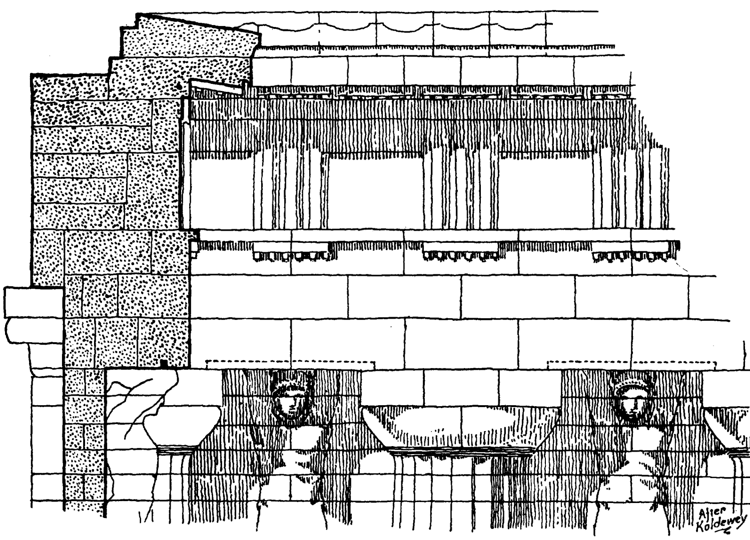

FIGURE 2.—ENTABLATURE OF OLYMPIEUM: ACRAGAS.

great length, about 26 ft. 7¾ inches between the centres of columns, was subdivided into three by vertical joints, one such joint coming exactly at the centre of the clear span (Fig. 2). While the intervals between the columns are filled with walls, the faces of these screen walls, in their upper portions at least, lay considerably behind the centres of the columns; and early attempts to restore the temple, on paper, did not make very clear

[1] It is the fact that the hard limestone superstructure was doweled to the bar that proves that the bar could not have been of wood, as was thought by earlier observers (*B.C.H.* 1910, p. 190; *B.C.H.* 1911, p. 160; *Berl. Phil. Woch* 1911, col. 1615). For my restoration of iron bars, see *B.C.H.* 1912, pp. 453–455.

the method by which the overhanging portion of the architrave would have been supported. For the architrave, with its joint at the centre of the free span, projected 6 ft. 7 inches beyond the face of the screen wall. It was here that the figures of Atlantes, 25 ft. 2 inches high, hitherto assigned to positions within the temple, were eventually located by Koldewey and Puchstein.[1] Even with this arrangement, which is undoubtedly the correct one, the outer face of the architrave remains unsupported. But along the lower surface of these outer architrave blocks runs a groove, 4 inches wide and 8½ inches high. Durm still regards this as a rope cutting for use while the blocks were being hoisted,[2] even though Koldewey and Puchstein had already pointed out the fact that the cuttings did not continue for the entire length of the stone, but reached only 21½ inches beyond the edge of the abacus, giving a total length of 14½ ft. Cockerell had thought that these cuttings were for beams of hard wood,[3] but Hittorff recognized traces of iron rust.[4] We have, therefore, a clear case of an iron beam laid across the interval between the capitals of the columns, with the stone superstructure built upon it. On account of the form of construction, this iron beam was necessarily in the exposed soffit of the stone architrave; but it would have been possible to conceal it by means of stucco. Thirty-eight of these beams would have been required in the peristyle.

At one point in the Erechtheum at Athens we find a similar form of construction: the lintel of the subterranean doorway leading to the crypt under the North Porch, though only 20 inches high and 3 ft. 6 inches wide, carries the entire north wall of the building across a span of 2 ft. 5 inches. This lintel was reinforced by inserting in its bottom an iron bar, sealed with lead while the lintel was still loose and upside down on the ground; the iron beam, furthermore, is still in place, and, therefore, its height and length cannot be ascertained. It would have been far better to have placed the iron in the top of the marble lintel, not merely because it would thus have been concealed from view (for in this subterranean doorway we are not concerned with

[1] Koldewey and Puchstein, *Die Griechischen Tempel in Unteritalien und Sicilien*, pp. 158–162.

[2] Durm, *Baukunst der Griechen* (1910), pp. 402–404.

[3] *Antiquities of Athens*, V, ch. I, p. 8 and pl. 5.

[4] Hittorff and Zanth, *Architecture antique de la Sicile*, pp. 310, 566, pl. 89, fig. 5.

finish), but because of a vital constructive defect. The marble, more brittle than the iron, naturally cracked before the weight of the superincumbent wall could be transmitted to the more flexible iron beam.

Far more scientific is the system adopted in the Propylaea at Athens. Here the Ionic architrave of the main hall is, in section, composed of two marble blocks each about 20 inches thick and 2 ft. 9½ inches high, set on edge, back to back. Each supports marble ceiling beams coming not merely above the Ionic columns but also exactly at the centre of the span (Fig. 3). The total weight of half of one of these ceiling beams with its load of coffers was 6⅜ tons. Here again the architect did not trust his marble. Therefore on the top of the Ionic architrave he cut a groove nearly 5½ inches deep and 3 inches wide, and half the length of the architrave, just 6 ft.; the groove has a shoulder cut at each end, about 3¼ inches long, and rising 1 inch above the bottom of the groove. In this groove, as was discovered by Mr. Balanos, the architect in charge of the modern reconstruction,[1] was placed a solid rectangular iron beam, which transmitted the weight of the central ceiling beam to the two shoulders 5 ft. 5½ inches apart, where it could be cared for by the capitals of the Ionic columns. It is to be noted that the length of the iron beam was made as short as would be consistent with this purpose; by terminating it at a distance of 3 ft. from each end of the architrave, it was possible to use a lighter section than would have been the case had the iron reached from end to end of the marble architrave. And since, in this interval between the shoulders, the groove was cut 1 inch deeper than the bottom of the iron beam, the latter, not being sealed with lead, was perfectly free to deflect under the weight of the marble ceiling beam. Of these iron beams, of which sixteen were employed in the hall, only the rusted traces now appear in the grooves. To ensure the transmission of the weight directly to the iron beam, two copper plates about 2 inches square were placed on the iron beam and upon these rested the marble beam; the stains of the copper are still visible on the bottom of the marble. The central portion of the Ionic architrave, therefore, supported nothing but its own weight.

Since in this case we know all the details of weights and dimensions, it may be of interest to quote the results. That the Greeks

[1] Balanos, *Actes du seizième Congrès International des Orientalistes*, 1912, p. 44; cf. Karo, *Arch. Anz.* 1912, p. 236.

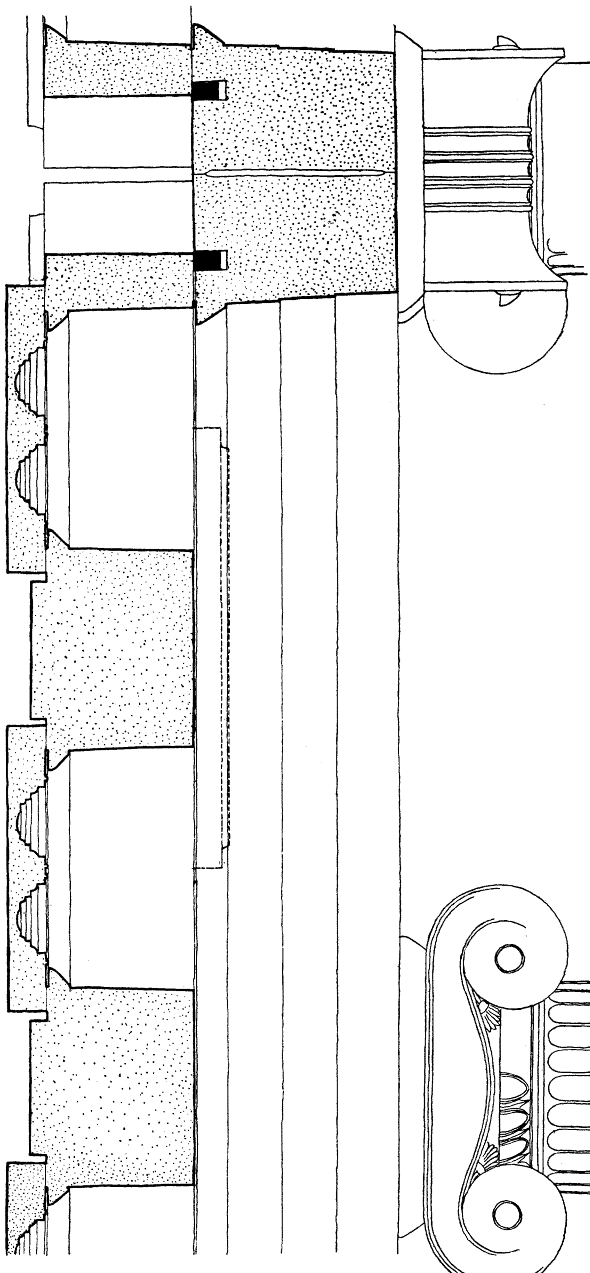

FIGURE 3.—IONIC CEILING OF PROPYLAEA: ATHENS.

were timid with regard to stone construction, and erred on the side of safety, is a fact that has long been apparent.[1] This is another case in point. If an Ionic architrave of this character were being erected at the present day, we should not object to a maximum fibre stress (the tension occurring in the outermost particles at the bottom of the architrave) amounting to as much as 120 pounds per square inch of section. Now if Mnesicles, the architect of the Propylaea, had taken no precautions at all, and had not inserted the iron beam, the maximum stress in the Ionic architrave would have been only 103 pounds per square inch, a stress with which the marble would have been quite able to cope.[2] But on account of timidity he inserted the iron beam, and thereby reduced the maximum stress in the marble to 57 pounds per square inch, about half of the modern allowance. Such was the stress in the marble below the iron beam, but how about the iron beam itself? Here modern practice would not justify a greater maximum stress than 12,000 pounds per square inch; in the Propylaea, however, the actual stress was 17,500 pounds per square inch. In iron, therefore, it would appear that Mnesicles was far from timid; but his timidity may be attributed to ignorance. There was, however, no question of collapse; he used one third rather than one quarter of the breaking strength of wrought iron.

It was with such marble ceilings that the Greek architects appear to have experienced the greatest difficulties, which they overcame, to their own satisfaction at least, by the use of concealed iron beams. The result, in the case of the Propylaea, was eulogized as follows by Pausanias: "The portal has a roof of white marble, and for the beauty and size of the blocks it has never yet been matched."[3] Let us now turn to another example which Pausanias regarded with almost equal admiration: at Bassae, as he states, is "the temple of Apollo Epicurius, built of stone, roof and all; of all the temples in the Peloponnesus, next to the one at Tegea, this may be placed first for the beauty of the stone and the symmetry of its proportions."[4] Again emphasis is laid on the employment of stone throughout, and with reason; for the temple at Bassae, the first work of Ictinus, dating from about 450

[1] Carpenter, *The Esthetic Basis of Greek Art*, pp. 159, 260.

[2] In the marble ceiling beams themselves the maximum fibre stress rose even to 185 pounds per square inch, considerably more than the limit of present day practice.

[3] Pausanias, I, 22, 4.

[4] Pausanias, VIII, 41, 7–8.

B.C., marks the beginning of the substitution of marble ceilings for the wooden ceilings hitherto used in external porticoes.

At Bassae, therefore, the marble ceiling was an experiment and in its design the timidity of the architect is quite apparent. The end porticoes, furthermore, are exceptionally deep, two full intercolumniations; for the columns and antae of the inner porches are aligned with the third column on each flank of the peristyle. As a result, the maximum clear span of the ceiling beams of the external portico, from the inner face of the entablature of the façade to the outer face of that of the pronaos, amounts to 13 ft. $2\frac{1}{4}$ inches. Now the ceiling beams, of marble, were assigned a width of 2 ft. $2\frac{3}{8}$ inches and a height of $12\frac{3}{4}$ inches, so that if they had been solid they would have weighed 5,460 pounds in the clear span; they carried, furthermore, ceiling coffers weighing (on the outermost beams) about 220 pounds per running foot, contributing an additional load of 2,900 pounds. Under such circumstances, the maximum fibre stress, the tension at the bottom of the ceiling beam, would have amounted to 231 pounds per square inch, twice as much as we should regard as permissible. Ictinus, too, was unfavorably impressed by the result, and attempted to remedy the situation by hollowing the tops of the ceiling beams, transforming them into mere shells, about 4 inches thick on each side and only $3\frac{1}{4}$ inches thick at the bottom (Fig. 4). In other words, he removed more than half of the section of the ceiling beam, reducing its weight, in the clear span, from 5,460 to 2,630 pounds.

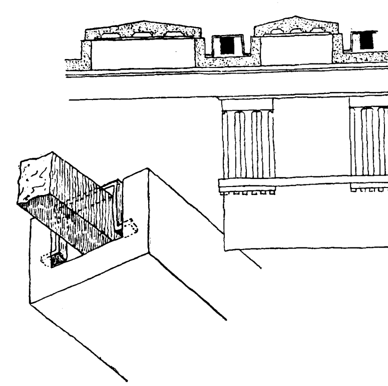

FIGURE 4.—PERISTYLE CEILING: TEMPLE AT BASSAE.

What was the exact purpose of this reduction of the weight? Cockerell, without further reflection, merely remarked that "these are hollowed, in order to diminish their weight . . . and secure their duration, which was not the case in those of the Propylaea."[1] But analysis of the resulting forces shows that by such a process Ictinus would not have improved the situation in

[1] Cockerell, *Aegina and Bassae*, pp. 51, 54.

the least. The beam is lightened, to be sure, but it is also weakened to such a degree that the maximum fibre stress is still 227 pounds per square inch, practically identical with what it was before the so-called precaution was taken. This is not the way in which a Greek would have worked; he would rather have retained the full section of the marble beam, stiffening it by adding a tall flange or ridge along the top which increased its height but was invisible from below. We must seek another explanation of the hollowing of the beam. And such an explanation is suggested by the striking similarity (of course not apparent to Cockerell) between this marble beam section and modern forms of terra-cotta and stone used for the casing of steel beams. At Bassae, as in so much of our modern work, we have apparent marble beams which were in reality mere shells, the true supports of the ceiling having been iron beams which formed their core. The purpose of the reduction of the weight, by omitting more than half of the section of the marble beam, was, of course, to diminish the load carried by the iron beam, so that this, in turn, could be made lighter. There must have been hangers or straps of some sort, in order to secure the marble casing to the iron beam. And of such iron beams, of simple rectangular section, about 15 ft. in length, there must have been eighteen examples at Bassae, or even more if we can follow Pausanias literally and assume that the ceilings of the inner porticoes and of the cella were likewise of marble. Of actual remains of these iron beams, however, we have no traces.[1]

Another type of iron beam employed by the Greeks is the cantilever, a beam of which one end is firmly imbedded in a wall, while the other end is unsupported, even though the load may be placed upon this free end. The load is counterweighted by the wall in which the other end is imbedded. The most notable examples occur in the Parthenon, where in the pediment floors we find, near the centre, grooves varying in width from $4\frac{1}{2}$ to 11 inches, extending from the face of the tympanum almost to the front edge of the cornice (Fig. 5). In some cases they are at right angles to the face of the tympanum, while others are oblique. There are five of these grooves in each pediment, all grouped near the centre; and their purpose obviously was to contain iron cantilever beams, which should support the heavier statues at the middle of the pediment, and thus take the weight off the overhanging portion of the

[1] The broken fragments of the hollowed marble beams should reveal, if carefully examined, traces of some method of attachment to the iron.

marble cornice.[1] In order to permit them to function in this manner, the cantilevers were laid directly on the top of the marble cornice, and ran back under the tympanum, according to the traces of rust, for 12 or 16 inches; to fit over them, corresponding cuttings were worked in the bottoms of the tympanum slabs, which thus straddled and firmly weighted the inner ends of the beams. It is from the cuttings in the tympanum blocks that we learn the height of the cantilevers, between 2½ and 5 inches.[2] Directly under the face of the tympanum, the pediment floor is sharply cut down to a depth of about 2 inches, and for a width corresponding to that of the iron cantilever; here, therefore, was the point of support of the cantilever, well inside the face of the entablature below. About 5 inches outside the face of the tympanum, and, therefore, practically over the face of the entablature below, is an additional drop of about ½ inch, so that the outer end of the cantilever was free to bend as much as 2½ inches before coming in contact with the cornice. Probably, however, they were not intended to bend so much; for we must assume that the marble statues did not rest loosely upon the cantilevers, but were grooved to a depth of about 1 inch to prevent lateral displacement; and thus if the cantilever were deflected even as much as 1½ inches the statue would begin to throw its weight upon the marble cornice. As it happens, the statues from the central portions of the pediments are not sufficiently preserved to reveal their adjustment to the cantilevers. Nor are the cantilevers themselves preserved; nothing now remains but the cuttings and the traces of rust. These cantilevers were concealed from view by the fact that they terminated about

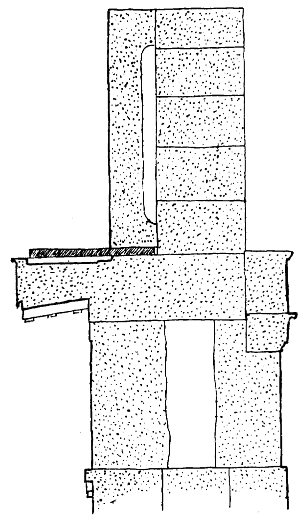

FIGURE 5.—PEDIMENT FLOOR OF THE PARTHENON.

[1] These beam cuttings are discussed by Penrose, *Athenian Architecture*, pp. 46–47, pl. 18; Michaelis, *Parthenon*, pp. 152, 172, 189, pl. 6–7; Sauer, *Antike Denkmäler*, I, pp. 49–51, pl. 58 A–C; Lethaby, *Greek Buildings*, p. 74.

[2] Two additional cuttings in the tympanum blocks of the west pediment, north of the five grooves, were apparently never used, since there are no traces of rust and no corresponding grooves in the pediment floor.

2 ft. 9 inches outside the face of the tympanum, and so about 5 inches behind the face of the cornice. But they were not protected from the elements, if we may judge from the abundant traces of rust; though possibly they were originally coated with molten lead.

Another example of cantilever construction is to be found in a late temple at Acragas, the so-called Temple of Castor and Pollux. Here the sima above the cornice is of remarkably heavy proportions; and since the material employed was a coarse limestone, elaborate precautions were taken lest the overhanging portion of the cornice be split off (Fig. 6). In the first place, the entire top of the cornice itself, from the nosing to a line about 16 inches behind it, was cut down to a depth of nearly $\frac{1}{2}$ inch. Then, to ensure the relief of the cornice, slender iron cantilevers, nearly $2\frac{1}{2}$ inches high, widening toward the top, were dovetailed at intervals into the bottom of the sima, running from back to front, or, in the case of the angle blocks, diagonally, but always terminating about $3\frac{1}{2}$ inches from the face of the sima in order that they might remain concealed.[1]

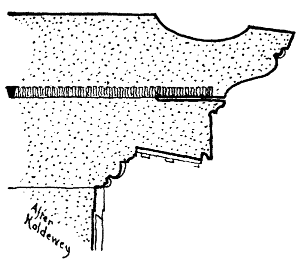

FIGURE 6.—CORNICE OF THE TEMPLE OF CASTOR AND POLLUX: ACRAGAS.

From these isolated instances it is possible to conclude that the Greeks did not hesitate, whenever they were doubtful of the stability of masonry, to employ concealed structural iron very much as we are doing in modern times. That they had any precise knowledge of the properties of wrought iron it is difficult to assume. For in the Propylaea, at least, they strained it beyond a limit which we should regard as justifiable, and this in order to relieve marble which was actually quite capable of supporting the load. It is, to be sure, false construction; it would not be commended by the purist; but the Greeks were, after all, quite human, and from the study of their experiments, their failures and subterfuges, we can learn almost as much as from their successes.

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[1] For this example, see Koldewey and Puchstein, *op. cit.* p. 179.